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Trends in tropical cyclones in the South Indian Ocean and the South Pacific Ocean

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[1] The statistical significance of trends in tropical cyclones (TCs) in the South Indian Ocean (SIO) and the South Pacific Ocean (SPO) has been examined. Calculation of significance is based on nonparametric Monte Carlo methods, and in addition we explore whether a constant model, a linear model, or a simple breakpoint model represents a best fit to the data. For the 1981–1982 to 2006–2007 TC seasons, there are no apparent trends in the total numbers of TCs (by which, in this study, we mean those tropical systems attaining a minimum central pressure of 995 hPa or lower), nor in numbers of 970 hPa TCs in the SIO and the SPO (such TCs being called severe in the Southern Hemisphere). Positive trends in the numbers of 945 hPa and 950 hPa TCs in the SIO are significant but appear to be influenced to some extent by changes in data quality. In the Australian region, no significant trends in the total numbers of TCs, or in the proportion of the most intense TCs, have been found.

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1. Introduction

[2] Trends in tropical cyclone (TC) occurrences and intensity, and possible physical mechanisms for change, have been discussed widely in recent years. *Webster et al.* [2005] reported that the global number of very intense TCs (Saffir-Simpson categories 4 and 5) had almost doubled over recent decades. Using the TC potential dissipation index as a measure of TC activity, *Emanuel* [2005] arrived at similar conclusions for two of the major TC basins: the North Atlantic and the northwest Pacific. Other authors have rejected these findings, mainly on the basis of the argument that changes have been so great in observation technologies and analysis techniques that the reported changes are artificial, and not due to any actual trends [*Landsea et al.*, 2006; *Chan*, 2006; *Kossin et al.*, 2007]. For the Australian region (AR) and the Southern Hemisphere (SH), trends have been reported in the number of TCs and in the proportion of very intense TCs by various authors, including *Nicholls et al.* [1998], *Harper et al.* [2008], and the current authors [*Kuleshov et al.*, 2008].

[3] It is well documented that the sea surface temperatures over the major TC basins have increased over recent decades [*Knutson et al.*, 2006; *Intergovernmental Panel on Climate Change*, 2007]. Theoretical and modeling studies would indicate that in response there should be a concomitant increase in the TC limiting upper intensity referred to in the literature as the maximum potential intensity [*Emanuel*, 1987; *Holland*, 1997]. There is substantial discussion, however, on the magnitude of the response and whether it should be distinguishable in current data where the signal to noise ratio may be small. The small signal to noise ratio in the data is due to a number of effects including (1) the large interannual variability of TC activity in each basin, (2) the fact that only a small fraction of TCs actually approach their maximum potential intensity, and (3) limitations in the underlying data.

[4] In our previous paper [*Kuleshov et al.*, 2008], we calculated trends in activity of TCs in the SH (the region south of the equator, 30°E to 120°W). In that study, as in the present work, by a TC we mean a tropical system that attains minimum central pressure of 995 hPa or lower. The earlier work used the best track data from the SH TC Warning Centres (TCWCs) over the TC seasons 1981–1982 to 2005–2006. We found no trends in the total numbers of TCs nor in the numbers of *severe* TCs (defined for this purpose as those having a lifetime minimum central pressure (LMCP) of 970 hPa or lower, which equates approximately to the lower bound of a category-three system in the Australian region). However, there was a significant positive trend in the occurrence of intense TCs with LMCP of 945 hPa or lower, significance being defined through standard linear regression methods.

[5] Through inspection of the data sets for their use in a study of statistical relationships between TC activity and sea surface temperatures [*McBride*, 2008], the authors learned that the increased occurrences of the strongest TCs around Australia may well be due to inhomogeneities in the data, as had been suggested by *Landsea et al.* [2006] for trends observed in the Northern Hemisphere. The current study reexamines the findings of *Kuleshov et al.* [2008]. There are three changes from our previous study. Because of identi-

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fied data problems, the SH data set was reassembled by combining the official best tracks (in their current state as of 2008) from each of the relevant Regional Specialised Meteorological Centres (RSMC). The second change is that we reexamine the statistical significance, on the basis of nonparametric Monte Carlo methods and the test of whether a constant model, a linear model, or a simple breakpoint model represents a best fit to the data. Third, trends are examined for a range of LMCP intensity thresholds. The purpose is to determine whether there are trends in the SH TC occurrence and intensity time series beyond what can be attributed to interannual variability and changes in observing procedure.

[6] The current study documents those trends that exist in the SH TC data set and in subsets for the Australian region, the Southern Indian Ocean (SIO), and the South Pacific Ocean (SPO). It also presents methodologies for determining the significance of such trends by nonparametric techniques. The data set used is the Southern Hemisphere Tropical Cyclone (SH TC) archive, which was compiled from the best track data sets of the National Meteorological and Hydrological Services with WMO (World Meteorological Organization) responsibility for TC forecasts and warnings across the SH, in consultation with these offices. A documentation of trends in this data set thus provides baseline information for detection and attribution studies toward projections of expected changes in TC activity under global warming.

2. Data and Methods

[7] Following the methodology of *Kuleshov et al.* [2008], trends are examined in two subbasins: the SIO and the SPO, the dividing line being through the Australian region at 135°E [*Kuleshov et al.*, 2009b]. A TC archive for the SH was updated in 2007 at the National Climate Centre, Australian Bureau of Meteorology [*Kuleshov et al.*, 2008] and subsequently revised in 2008 (as discussed in section 4). The archive now consists of best track data for the TC seasons 1969–1970 to 2006–2007. However, the period of complete records of estimated TC intensity is shorter (from the 1981–1982 season). The revised SH TC archive presently contains 686 identified systems in the 26 TC seasons from 1981–1982 to 2006–2007. Four of these systems do not have assessed LMCPs at or below 1000 hPa. For the remaining TCs, we have assigned them spatially (e.g., to the SIO or the SPO, following *Kuleshov et al.* [2009b]) according to the position at which the LMCP is *first* assigned. (Some TCs are analyzed as maintaining their LMCP over several hours.) These positions consist of latitudes and longitudes in degrees resolved to one decimal place.

[8] The statistical significance of the linear trends in the various TC time series is assessed in two ways. We have not used the standard linear regression approach, on the basis of assumption of identically independently normally distributed residuals, as the TC data, being (nonnegative) integers, depart considerably from this assumption. Rather, we have calculated the statistical significances by Monte Carlo simulation (10,000 iterations) involving resampling the time series *with* and *without* replacement and forming a sampling distribution of the linear trend from which we determine the significance level. The linear trend significances are calculated in the two-tailed form, and we (conservatively) take the overall significance of the trend to be the larger of the two assessments.

[9] We have also subjected the TC time series to a single breakpoint testing procedure. This is a nonparametric procedure on the basis of the Mann-Whitney statistic [*Pettitt*, 1979] and is somewhat analogous to the better known parametric procedure on the basis of the null hypothesis that the data are normally distributed (using the pooled variance t statistic for assessing the difference in means between two samples [e.g., *Moore and McCabe*, 1993]), the nonparametric approach being more appropriate given the characteristics of the data. The most probable location for a single positive (or negative) break is obtained by carrying out the Mann-Whitney-Pettitt test for every possible breakpoint, subject to the constraint of a minimum of four TC seasons either side of the break. It is chosen as the one that gives the most extreme value of the test statistic. Statistical significances were calculated by the Monte Carlo simulation, sampling from the time series with and without replacement (10,000 iterations).

[10] One motivation for the use of breakpoint analysis is that it can help identify artificial changes in the data that might not be evident in trends or raw time series. The two most critical issues impacting on the homogeneity of TC records, and the associated confidence in climate change analyses, are changes in analysis practice and changes in the quality of the data. If step changes in the TC data coincide with known changes in the quality and abundance of data and associated TC analysis practices, then a case might be made that the change is artificial. (It should be noted however that the breakpoint assessment procedure may lead to the rejection of the null hypothesis (of no change) in time series with strong linear trends, even though a visual inspection of the data indicates the absence of a break. In such cases the most plausible "breakpoint" is typically in the middle of the time series.) Step changes (apparent or real) in the TC data over the basins of the SH might also arise through variability in low-frequency climate modes such as El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation, and the Indian Ocean Dipole, but attribution of these changes to such climate modes is beyond the scope of this study.

[11] The major purpose of the breakpoint analysis is to contribute to the assessment of statistical significance and interpretation of any trends that are found in the data. In this context, for each series, we compare three competing models (constant, linear, step change) under leave-one-season-out cross validation, to determine which of the three models generates the least root-mean-square error. The step-change model has its change at the most likely breakpoint as defined above. If a linear trend is observed in a TC time series, but the series is better represented by a constant model under the cross-validation process, we consider the trend to be insignificant and attributable to noise or interannual variability, particularly so if the constant model is also better than the breakpoint model.

3. Results

[12] In this study, TC occurrences were based on the existence of an LMCP of 995 hPa or lower, which equates

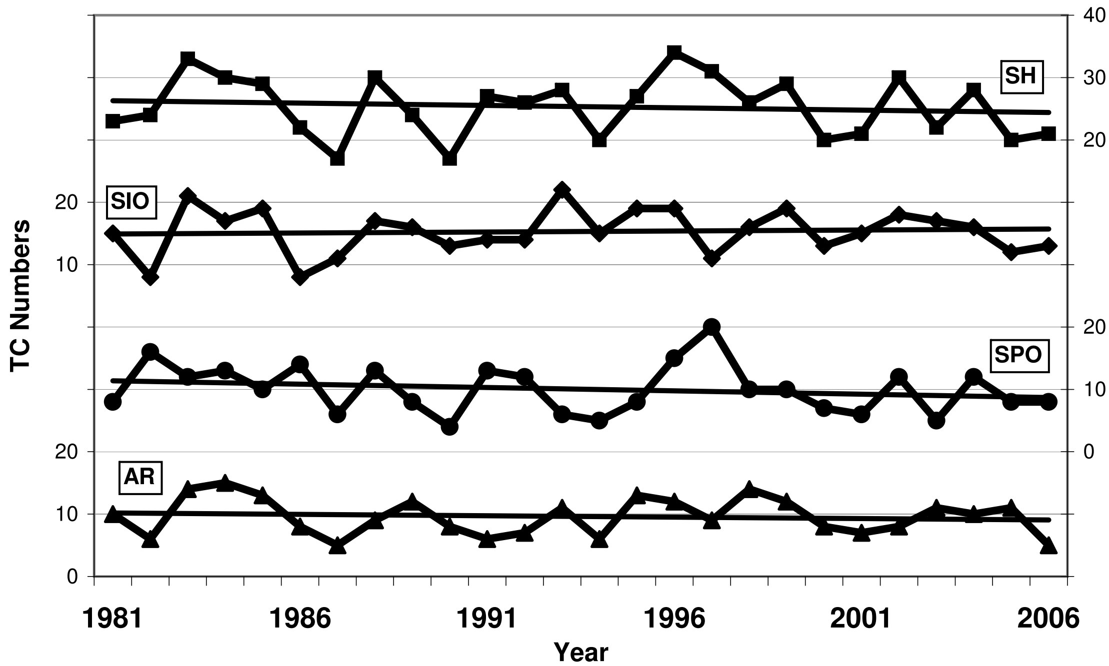

Figure 1. Annual numbers of TCs with LMCP of 995 hPa or lower for the SH (squares, right axis), SIO (diamonds, left axis), SPO (circles, right axis), and AR (triangles, left axis), 1981–1982 to 2006–2007 seasons, with linear trends.

approximately to a weak category-one tropical cyclone in the SH. Six additional thresholds were employed (945, 950, 955, 960, 965, and 970 hPa), to explore the consistency of the results for severe TCs, following *Nicholls et al.* [1998], who used 970 hPa as the threshold for severe TCs in the SH. Even though the uncertainty in the LMCP may exceed 5 hPa, operational procedures in the SH have been such that importance was placed on particular thresholds (e.g., 950 hPa; this issue is discussed further in section 4), motivating our choice of these thresholds in an attempt to determine the robustness of any trends in the presence of such threshold-dependent operational procedures.

[13] For the two SH basins (SIO, SPO), the analysis is restricted to the period from 1981–1982 onward (26 seasons). The AR subdomain has complete intensity records from 1969–1970 (38 seasons). It is worthwhile examining trends separately over this region as the three relevant TCWCs responsible for the best tracks (Darwin, Perth, and Brisbane) are all part of the Australian Bureau of Meteorology, thus ensuring some level of consistency in operational procedures and detection methodology.

3.1. Australian Region: 38 Year Time Series

[14] For the complete series of 38 years, the trends in annual numbers of TCs in the AR (90°E to 159.9°E) attaining an LMCP of 995 hPa or lower is negative (-0.055 TCs yr^{-1}). The western AR (90°E to 134.9°E) has a trend of -0.017 TCs yr^{-1}, while the eastern AR (135°E to 159.9°E) has a trend of -0.038 TCs yr^{-1}. For none of the three regions (AR, western AR, and eastern AR) is this trend significant at the 10% level (two-tailed).

[15] Trends in the proportions reaching severe intensities are uniformly positive across the range of studied thresholds. However, they are significant at the 6% level only for the lower thresholds (950 and 945 hPa), and then for the AR and western AR but not for the eastern AR. The results for the AR mirror those of the western AR due to it being climatologically more active than the eastern AR. For the proportion reaching an intensity of 950 hPa, the step-change model is the best fit to the data for the AR and western AR, with a constant model being best for the eastern AR. For the western AR, the breakpoint analysis indicates a significant increase (<1% one-tailed) in the proportion of intense TCs around 1977 across a range of thresholds (945–960 hPa), which corresponds closely to geostationary satellite imagery becoming available in the AR in 1978 [*Harper et al.*, 2008]. This suggests data inhomogeneity as a contributing factor to the observed trend, although the ENSO shift at much the same time (e.g., *Power and Smith* [2007]) may also be relevant.

3.2. Southern Hemisphere Ocean Basins: 26 Year Time Series

[16] Changes in TC occurrences in the SH, the SIO, and the SPO were analyzed over the 26 seasons 1981–1982 to 2006–2007. Over this period, there are no significant trends in the annual numbers of TCs (SPO, SIO, SH) attaining an LMCP of 995 hPa or lower (Figure 1), and under cross validation the constant model ($N(t) = a$) is a better fit than the linear model ($N(t) = a + bt$) for all three regions.

[17] For (970 hPa or lower) severe TCs (Figure 2), there are no significant trends in the SIO and the SH, although the declining trend (-0.096 TCs yr^{-1}) in the SPO is borderline significant (11% two-tailed). This is matched by the cross-validation modeling: The constant model is the better fit for the SIO and SH, but the linear model is better for the SPO.

[18] For the most intense (950 hPa or lower) TCs (Figure 3), there is no significant trend in the SPO, but the trends are significant in the SIO (+0.15 TCs yr^{-1}; 1% two-tailed) and in the SH as a whole (+0.14 TCs yr^{-1}; 3%

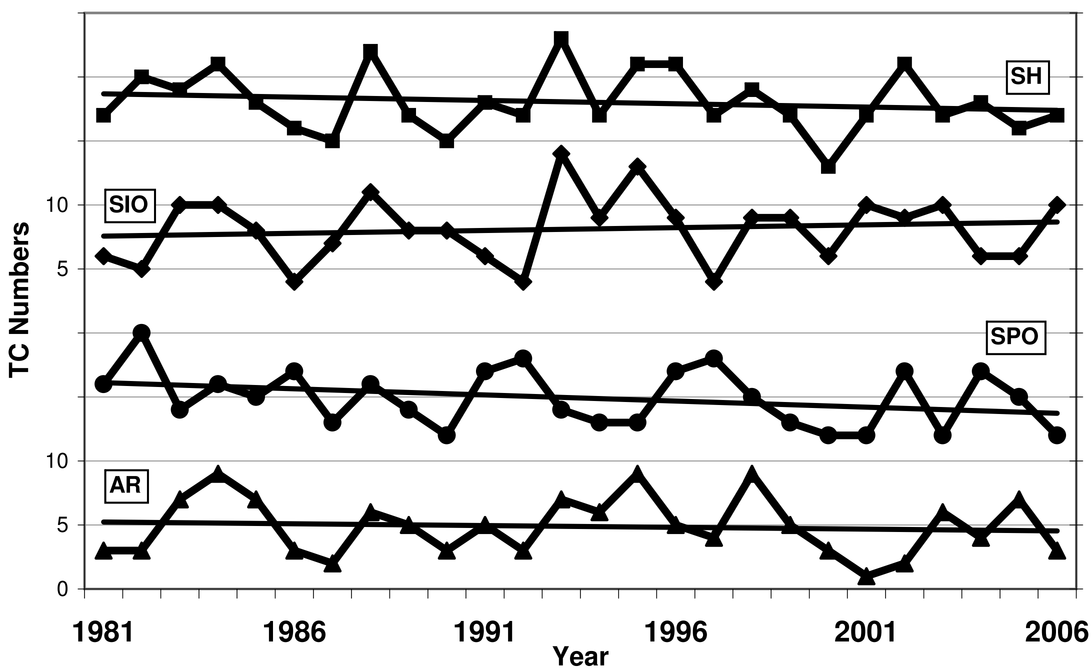

Figure 2. Annual numbers of TCs with LMCP of 970 hPa or lower for the SH (squares, right axis), SIO (diamonds, left axis), SPO (circles, right axis), and AR (triangles, left axis), 1981–1982 to 2006–2007 seasons, with linear trends.

two-tailed). Similar results were obtained in the annual 945 hPa counts but not in the 955 hPa counts.

[19] These trends in the most intense TCs are even more significant when assessed in terms of the annual proportions of TCs which reach these higher intensities. The apparent increase in the numbers of intense TCs also leads to the rejection of the null hypothesis of no change when assessed in terms of possible single-break step changes. From such an assessment, the most plausible location for a single rising step change (if one exists) in the SIO annual counts is between the 1992–1993 and 1993–1994 seasons; see Table 1, which shows the results of the nonparametric positive single-

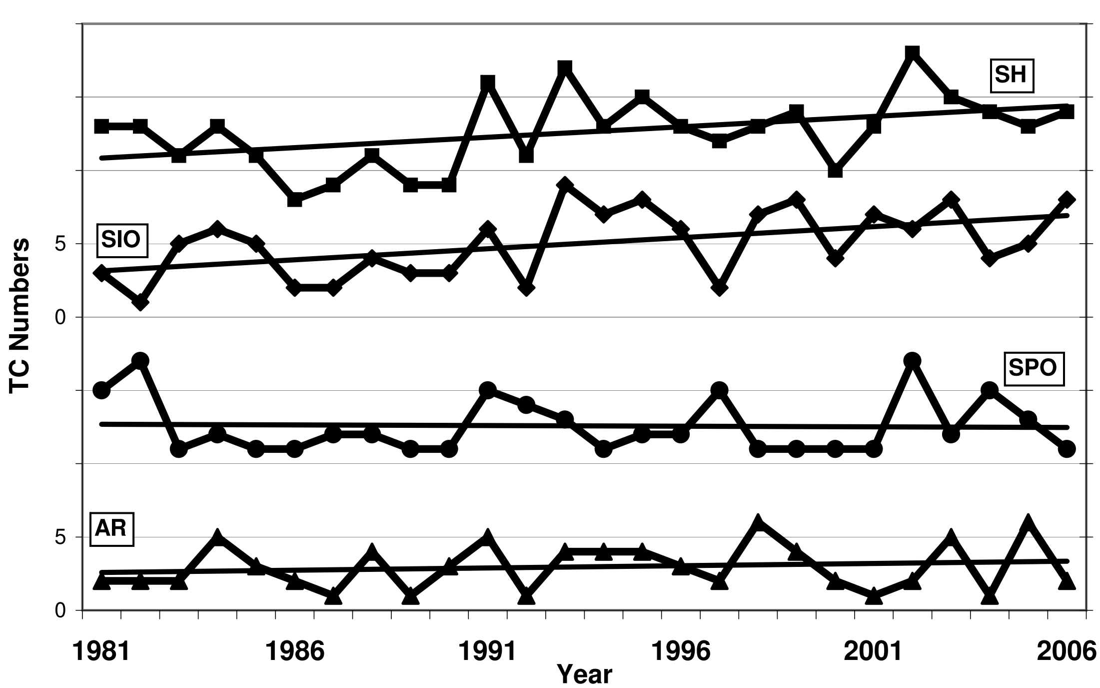

Figure 3. Annual numbers of TCs with LMCP of 950 hPa or lower for the SH (squares, right axis), SIO (diamonds, left axis), SPO (circles, right axis), and AR (triangles, left axis), 1981–1982 to 2006–2007 seasons, with linear trends.

Table 1. Single Breakpoint Assessment, Nonparametric, for Severe TC Numbers Over the Period 1981–1982 to 2006–2007, and Ratios With Respect to the 995 hPa Level[a]

	WSIO		ESIO		SIO		SPO	
Intensity (hPa)	Break	Significance	Break	Significance	Break	Significance	Break	Significance
945	1993	0.17	1985	**0.03**	1993	**0.01**	2002	0.43
(Ratio)	1993	0.08	1985	**0.01**	1991	**0.02**	2002	0.25
950	1993	**0.02**	1993	0.36	1993	**<0.01**	2002	0.39
(Ratio)	1993	**<0.01**	1985	0.31	1993	**<0.01**	2002	0.25
955	1988	0.39	1993	0.57	1993	0.18	2002	0.61
(Ratio)	1999	0.07	1986	0.51	1993	0.10	2002	0.34
960	1999	0.32	1993	0.41	1993	0.17	2002	0.69
(Ratio)	1999	**0.05**	1987	0.59	1993	0.07	2002	0.52
965	2001	0.36	1993	0.37	1993	0.08	1991	0.74
(Ratio)	2000	0.10	1993	0.46	1993	**0.03**	1990	0.49
970	1987	0.42	1993	0.56	1993	0.33	none	
(Ratio)	2000	0.49	1993	0.64	2001	0.63	2002	0.86

[a]The "break" columns indicate the location of the most plausible upward step (e.g., 1993 denotes a break between the 1992–1993 and 1993–1994 seasons). Significances are one-tailed (values less than 0.05 are given in bold type) and indicate the larger of the two values obtained by Monte Carlo simulation (10,000 iterations) sampling with and without replacement. Abbreviations: WSIO, western South Indian Ocean; ESIO, eastern South Indian Ocean; SIO, South Indian Ocean; and SPO, South Pacific Ocean.

breakpoint assessment for a range of intensity thresholds between 945 and 970 hPa over the period of data with complete intensity records. This break is significant in the 945 hPa (1% one-tailed) and 950 hPa (<1% one-tailed) levels and appears in the 955, 960, 965, and 970 hPa levels (although without attaining statistical significance). It is also significant in the 945–995 hPa (2% one-tailed) and 950–995 hPa ratios (<1% one-tailed). This leads us to the supposition that *at least some* of the apparent increase in frequency of the most intense storms in the SIO (and by extension, the SH) may not be real, arising from changes in TC monitoring and analysis techniques. This supposition will be supported by a consideration of data quality issues (section 4), but to further test the hypothesis, we have split the SIO data into the western (30°E to 89.9°E, the RSMC La Réunion's area of responsibility) and eastern (90°E to 134.9°E, the TCWCs of Perth's and Darwin's areas of responsibility) subregions. Results for these two subregions are also given in Table 1, along with results for the SPO. The year 1993 emerges in the breakpoint assessment of the SIO much more clearly than it does in either of the two western SIO and eastern SIO subregions, but it is still present to some extent in those subregions. (Splitting the SIO region in this way may simply be decreasing the signal to noise ratio.)

3.3. Southern Hemisphere Ocean Basins: 14 Year Time Series

[20] We have also looked at trends in the last 14 years (1993–1994 to 2006–2007), the period for which the intensity estimates would appear to be the most reliable (as measured by availability of satellite imagery and consistency of operational procedures, discussed in section 4). The trends in TCs for the SIO, western SIO, and eastern SIO are all negative, but only the SIO trend is marginally significant (9% two-tailed). Trends in the proportions reaching 970 and 950 hPa are not significant, and the constant model provides the best fit of the three models for these three regions (excepting the SIO 970 hPa fraction case). For the SPO and SH, the trends in TCs are also negative but not significantly so and the constant model provides the best fit. Trends in the proportions reaching 970 and 950 hPa are likewise not significant, and only one significant break is detected (a rising SH 950 hPa fraction, 5% one-tailed). In relation to these results, 14 years is a rather short period over which to be assessing the statistical significance of linear trends and, as the length of the time series is taken into account in the estimation of trend significance, trends would have to be relatively strong to attain significance. The presence in these data of real trends, which are not statistically significant (because of the shortness of the time series), cannot be excluded, but in the absence of additional information (e.g., more years of data) it is difficult to distinguish between the effects of sampling variability and real trends.

3.4. Australian Region: 26 Year Time Series

[21] Analyzing changes in TCs in the AR over the 26 year period (1981–1982 to 2006–2007), there were no significant trends in the numbers of TCs, and under cross validation the constant model describes the data the best for the western AR, the eastern AR, and the whole AR.

[22] Trends in the proportions reaching severe intensities are positive in the western AR and negative in the eastern AR. In the western AR (in effect the eastern SIO region in Table 1), the location for the most plausible positive break lies around 1985–1987 at the lower LMCP thresholds (significantly so for the 945 hPa threshold) and 1993 for the upper thresholds. As with the SIO, this may indicate some residual data inhomogeneity and motivates an assessment of the trends over the last 14 years (see below). In the eastern AR, the location for the most plausible negative break in the 26-year time series lies around 1996–1998, sometimes with borderline significance. This placement in the middle of the time series may just reflect the general negative trend in the proportions reaching severe intensities, without being indicative of a change in observational practice. The best model for the eastern AR fractions is the constant model for some thresholds and the falling step-change model for the others.

3.5. Australian Region: 14 Year Time Series

[23] Over the 14 year period, trends in TC numbers are negative for the western AR, the eastern AR, and the AR, but not significantly so. The cross-validation modeling suggests the constant model in all three regions describes these data the best. Trends in the proportions reaching

Table 2. Trends in TC Numbers and in the Proportion of Severe TCs Reaching the Intensities of 945 and 955 hPa for Various Subsets of the SH Basin Over the TC Seasons 1969–1970 Through 2006–2007[a]

	AR (38 years)	SH (26 years)	AR (26 years)	SIO (26 years)	SPO (26 years)	AR (14 years)	SIO (14 years)	SPO (14 years)
Trend in total cyclones	−2.1 TCs per 38 years	−2.0 TCs per 26 years	−1.2 TCs per 26 years	+0.8 TCs per 26 years	−2.8 TCs per 26 years	−2.7 TCs per 14 years	−5.1 TCs per 14 years	−0.9 TCs per 14 years
Significant at 5%	No	No	No	No	No	No	No	No
Best model	**SC**	C	C	C	C	C	**L**	C
Trend in proportion LE 955 hPa	+18% per 38 years	+6% per 26 years	+3% per 26 years	+14% per 26 years	−4% per 26 years	−18% per 14 years	+2% per 14 years	+1% per 14 years
Significant at 5%	No	No	No	No	No	No	No	No
Best model	**SC**	**SC**	C	**L**	C	**SC**	C	C
Trend in proportion LE 945 hPa	+26% per 38 years	+17% per 26 years	+18% per 26 years	+28% per 26 years	+2% per 26 years	−3% per 14 years	+9% per 14 years	+5% per 14 years
Significant at 5%	**Yes**	**Yes**	No	**Yes**	No	No	No	No
Best model	**SC**	**L**	**L**	**L**	C	C	C	**SC**

[a]Trends that are statistically significant by the tests described are in bold. Also, any time series where a step-change (SC) or linear (L) model fits the data better than a constant (C) model is in bold. Abbreviations: AR, Australian region; SH, Southern Hemisphere; SIO, South Indian Ocean; and SPO, South Pacific Ocean.

severe intensities are also uniformly negative in all three regions, although not reaching significance at the 10% (two-tailed) level. The cross-validation modeling suggests the constant model for the western AR at five of the six thresholds. In the eastern AR and the AR, the modeling suggests the constant model for the most intense TCs of 950 hPa and below.

[24] Prior to the discussion, it is convenient to summarize some of the major results of this section. This is done in Table 2 and Figure 4.

4. Discussion

[25] The data used in the above analysis are composed of the official postseason best tracks compiled by the meteorological agencies with official WMO responsibility for forecasts and warnings across the SH, combined into a single archive at the National Climate Centre [*Kuleshov and de Hoedt*, 2003; *Kuleshov et al.*, 2008].

[26] As mentioned in section 2, an examination of the SPO TC data revealed apparent problems with the estimation of TC intensities in the area east of 160°E, with an artificially small number of TCs intensifying below 950 hPa prior to the late 1990s. For the period 1980–2000, 61 TCs were reported to have an LMCP below 955 hPa but only 8 below 945 hPa. This imbalance indicated that for a time 950 hPa was considered a lower limit in either operational procedures or in the postseason compilation of best tracks. To address this issue, the SH TC archive was recompiled

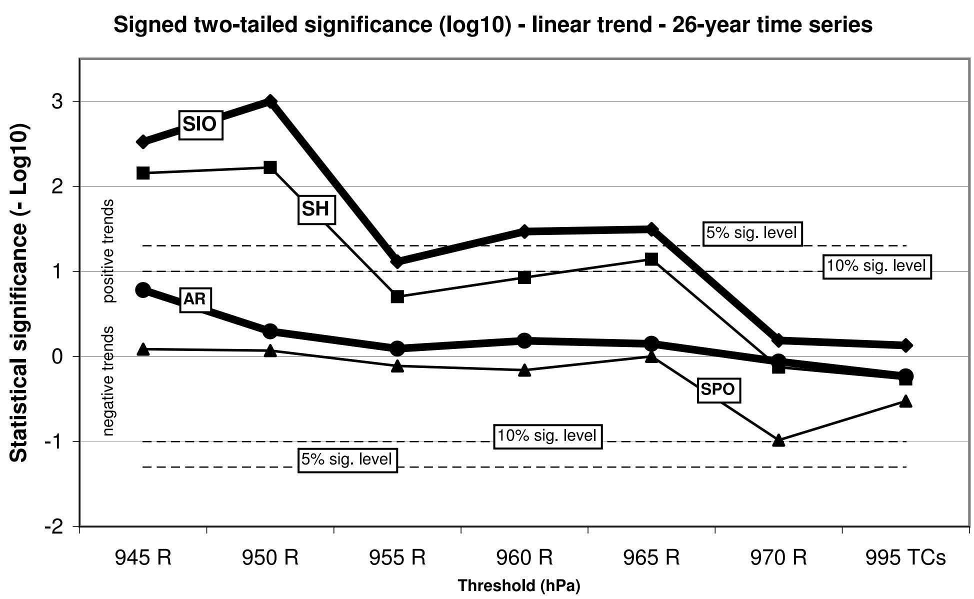

Figure 4. Significances (two-tailed; see text for further details) of the linear trends over the 26 year period 1981–1982 to 2006–2007 for four regions (SH, SIO, SPO, and AR, as indicated). Significances are shown for the trends in TC numbers (995 hPa TCs) and trends in the proportions of TCs reaching higher intensities (945, 950, . . ., 970 hPa, indicated by "R" on the horizontal axis). The significances are plotted logarithmically (base 10), signed according to the sign of the trend. Points closer to (farther away from) the zero line indicate less (more) significant trends. Also plotted are the 5% and 10% (two-tailed) significance levels.

and now consists of the best track data for the AR (as revised by *Trewin* [2008]), together with the most recent best track data provided by Météo-France (La Réunion, area west of 90°E) and the Meteorological Services of Fiji and New Zealand (area east of 160°E).

[27] In our previous paper, we reported significant trends in the proportion of TCs exceeding 945 hPa in intensity in both the SIO and the SPO over the 26 year period. As a result of the revision, the SPO trend is no longer significant. However, the significance of the trend remains in the SIO data, and thus in the total SH data. Although these two linear trends satisfy the three significance tests employed here (<1% two-tailed), as they likewise do for the 950 hPa threshold, there are reasons to believe changes in data availability and/or analysis procedures may be contributing factors, as discussed in the following paragraphs. Significance does persist in the proportions at the higher thresholds for the SIO (7% at 955 hPa, 3% at 960 hPa, and 4% at 965 hPa), but much less so in the SH (only 8% at 965 hPa) and not at all in the AR over the same period. The breakpoint analysis (Table 1) indicated a significant breakpoint in the SIO during in the early 1990s. The sharp decline in statistical significance in the SIO trend from the 950 hPa threshold to the 955 hPa threshold, and its partial recovery at the 960 and 965 hPa thresholds (Figure 4), indicates some measure of data inhomogeneity around the 950–955 hPa thresholds, although arguably not enough to explain away the significance of the trend in its entirety. Figure 4 also suggests a measure of data inhomogeneity around the 965–970 hPa thresholds in the SPO but not in the AR.

[28] Referring to the summary of trends in Table 2, trends in TC numbers are generally negative (or downward) across all basins over the three periods of study (38, 26, and 14 years); though in no case is this downward trend significant. Conversely, trends in the proportion of most intense TCs (945 and/or 955 hPa) are generally positive and as discussed above attain statistical significance for the SIO and for the SH as a whole. An upward trend in the intensity of the strongest TCs is the expected response to the warming oceans according to theoretical and modeling research [*Emanuel*, 1987; *Knutson and Tuleya*, 2004].

[29] Worldwide, the underlying technique for determining TC intensity is the Dvorak analogue procedure on the basis of patterns of infrared brightness temperature [*Dvorak*, 1984; *Velden et al.*, 2006]. The original version of the technique, applied to visible satellite imagery, was published in 1975, with its present form, on the basis of digital infrared imagery, published in 1984. It was only during the mid-1980s that high-resolution multichannel imagery became available at the AR forecast offices. In addition, supplementary data sources have increased during the past 26 years, including deployment of automatic weather stations along the Australian coastline and on small islands, and the advent of satellite-based scatterometer surface wind estimates. Various authors have discussed the potential impact of these changes on our ability to accurately determine the intensity of the more intense TCs, including *Trewin* [2008] and *Harper et al.* [2008]. On a global basis, the impact of data quality on our ability to determine trends has been discussed by *Landsea et al.* [2006]. A further compounding issue is that during forecast operations, the Dvorak technique output and the classification of TCs into intensity classes are both based on estimated sustained wind speeds. Intensity in terms of central pressure is then obtained through a wind-pressure relationship. Different wind-pressure relationships are in use in different forecast offices and warning centers across the SH [*Knaff and Zehr*, 2007; *Harper et al.*, 2008], and there have been changes in the wind-pressure relationships used through the period of study. The importance of this for determination of trends is that the SH track archive (in its current state) contains only the derived central pressure information and does not contain the wind-speed intensity estimates used operationally.

[30] For the western SIO where the tracks are maintained by Météo-France (La Réunion), operational meteorologists consider the intensity data insufficiently reliable for trend estimation prior to the establishment of the RSMC La Réunion in 1993 (P. Caroff, personal communication, 2009). The improvement in the quality of the SIO intensity data is consistent with the breakpoint calculations for that region (Table 1). (A further improvement in data quality occurred with the beginning of geostationary satellite coverage in 1998, as a result of the launch of the MeteoSat-7 satellite [*Kossin et al.*, 2007].)

[31] In identifying TC positions and estimating intensities, operational forecasters from Fiji and New Zealand (responsible for the eastern SPO tracks) faced similar challenges, through gradually improved observational data and understanding of TC development (S. Ready, personal communication, 2009). Within the satellite era, low-resolution geostationary satellite imagery for the South Pacific (west of about 155°W) became available to those forecasters from 1980. However, only from the early 1990s, with high-resolution imagery from the GOES-West satellites now available to the RSMC Nadi (established in 1993), did the Dvorak technique become increasingly used for estimating storm intensity. Throughout the 1980s and in the first half of the 1990s, there still was a reluctance to assign intensities beyond 80 kt (central pressures below about 955 hPa). From the mid-1990s, as forecasters in Fiji became more proficient at the Dvorak technique, there was a greater range of intensities assigned in TC warnings. It appears that for the SPO east of 160°E the most reliable estimates of TC intensity start in the early 1990s, with reliable estimates of LMCP of the most intense TCs from the mid-1990s. It is likely that prior to this time the number of TCs with reported intensities below 950 or 945 hPa in the eastern SPO is underestimated.

[32] While some of the trends in the TC data appear to be artificial to a degree, because of changes in TC observation practices and analysis techniques as discussed above, it is possible that TC occurrences are subject to variability associated with low-frequency climate modes, such as ENSO [e.g., *Kuleshov et al.*, 2008, 2009a], the Indian Ocean Dipole [e.g., *Chan and Liu*, 2009], and the Pacific Decadal Oscillation [e.g., *Goh and Chan*, 2009], to the extent of having a noticeable impact on the trends. The inclusion of these low-frequency climate modes in the trend analysis is beyond the scope of this study but will be a topic of further investigation.

5. Summary

[33] In this paper, we have reexamined trends in Southern Hemisphere tropical cyclone activity using a revised data set

of SH TCs and nonparametric methods for assessing trend significance. In addition, we have looked for possible breakpoints in the TC time series, using a single breakpoint testing methodology and performed a model-fitting comparison among three different types of simple statistical models (constant, linear, and single breakpoint).

[34] For the 1981–1982 to 2006–2007 period, there are no apparent trends in the total numbers of TCs reaching minimum central pressures of 995 hPa or lower, nor in the numbers of severe TCs in the five subdomains of the SH examined. Positive trends in 945 and 950 hPa TCs in the South Indian Ocean (and consequently the SH) are statistically significant (Figure 4). The breakpoint analysis (section 3) and the qualitative discussion of changes in data availability and in operational procedures (section 4) would suggest that these trends are influenced to some extent by changes in data quality. However, given the theoretical expectation that the response to the warming oceans will be in the number of most intense cyclones, it is also possible that the trends are indicative of this physical effect. Trends over the period for which the data are most reliable (approximately 1993–1994 onward) are for the most part not significant, the downward trend in South Indian Ocean 995 hPa TCs being the exception, although the shortness of this period makes it difficult for trends to attain significance.

[35] Changes in TC occurrences in the Australian Region were analyzed for three periods (1969–1970 to 2006–2007, 1981–1982 to 2006–2007, and 1992–1993 to 2006–2007 TC seasons). There are no apparent trends in the total numbers of TCs in the AR. Positive or negative trends in occurrences of severe TCs were identified over the different periods; however, these trends are not statistically significant and cross-validation modeling suggests the constant model describes the data the best.

[36] The aim of this paper is to present a concise study with the purpose of determining whether there are trends in the SH TC occurrence and intensity time series beyond what can be attributed to interannual variability and changes in observing procedure. A primary concern of such a study is that of data inhomogeneity. Some earlier studies have been based on the global Joint Typhoon Warning Center best track data set [e.g., *Webster et al.*, 2005], while others have used data derived from an archive of satellite records developed specifically to address the data inhomogeneity problem [*Kossin et al.*, 2007; *Elsner et al.*, 2008].

[37] Accordingly, an emphasis in this current paper has been a documentation of the quality of the best track TC data sets and their limitations. In this context, one of the journal's reviewers thought that the data quality issues had been overemphasized in the interpretation of trends and breakpoints, together with an underemphasis in the potential influence of climate modes (e.g., the ENSO and the Pacific Decadal Oscillation) and possible nonstationarity in environmental pressure. The concern is of particular relevance because the metric for intensity in the SH TC data set is central pressure and so may be influenced by climate-mode-driven variations in the surrounding or basin-scale pressure. We agree with the reviewer's position that the influence of climate modes on TC trends is one of importance, but our aim here has been to document the trends that exist. The role of climate modes in producing (or countering) trends, together with the impacts of changes in environmental pressure, will be the subject of further studies.

[38] The findings of the current study are important as the data set used constitutes the official best track data archive for the SH, even though there are uncertainties in TC intensity estimates (mainly prior to the 1990s, as discussed in section 4). In the case of the SPO, this has led us to avoid drawing conclusions on long-term (26 year) trends, although this basin still contributes to the broader SH trends reported above. Despite all this, the archive in our opinion represents the current best estimate of recent SH TC climatology. Attempts have been made to prepare consolidated global data sets [e.g., *Chu et al.*, 2002; *Kossin et al.*, 2007; *Kuleshov et al.*, 2008], and there are plans to continue these efforts [e.g., *Diamond et al.*, 2008; *Kruk et al.*, 2009]. However, consolidation of historical data from various regions is currently limited by the inhomogeneity of TC observation and analysis practice, and there is evidently a considerable need for reanalysis of the historical TC data in order to obtain globally homogeneous records. These homogeneity issues place limits on our ability at the present time to answer the important question of how TC activity is changing and its possible relationship to global climate change more generally.

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